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Hose Reinforcement Analysis

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Abstract

Hose design has been neglected as an engineering topic. Hose Technology, 2nd ed., Colin W. Evans, applied science publishers, Essex, England, 1979; has been cited as a design resource. This paper recommends a correction to the Evan's design equation. The hose nipple and hose tube inside diameter determine the forces the reinforcement has to support.

Introduction: This paper documents how to determine the hydrostatic forces developed within the hose construction.

Method/Approach: The articles use a conventional force balance approach. This paper uses force balances to show how the forces and the reinforcement geometry align to establish equilibrium. The assumption of the hose design equation requires the forces, **R**, to be equally distributed among the reinforcement strands. The number of strands, N, is empirically determined.

Conclusion: The forces are developed at the wetted surfaces and those forces must be supported by the reinforcement.

Key words: Hose reinforcement design; Hose internal force balance; Hose internal forces at the wetted surfaces

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INTRODUCTION

A simple hose assembly consists of two fittings and the hose segment consisting of the tube and reinforcement. (We will ignore other features such as the protective cover for this analysis.) The tube contains the fluid and the reinforcement constrains the tube. The hose segment has fittings on both ends to complete the hose assembly; the fittings are inserted into the hose segment and a collar or socket fastens the fitting to the reinforcement; and the fittings connect the hose assembly to the fluid system.

The Colin Evan's book ***Hose Technology***[1] is a standard reference and offers an analysis and a design approach that has worked well. There has been no reason to question the analysis. Then, a concern came up. What happens to a design when we have a different tube wall thickness? ..and none of the other design parameters related to operating pressure or the fitting nipple diameter have changed. The reinforcement sits at a different diameter (D_m) however the hydrostatic forces are the same. What is going on? Consider the following:

1. EVANS HOSE REINFORCEMENT ANALYSIS APPROACH

The Colin Evans book ***Hose Technology*** is a respected resource found in many hose manufacturing engineering libraries and similar reinforcement engineering design approaches are repeated in several other resources[2]. In Chapter 7, Evans presents the free body diagram (FBD) along with an analysis of the forces for the creation

[1] **Hose Technology, 2nd ed., Colin W. Evans, applied science publishers, Essex, England, 1979** chapter 7, *Hose Design and Construction*. Evan's develops the force balances that govern hose reinforcement response to hydrostatic forces. He suggests applying the forces at the mean braid diameter rather than at the nipple's outside diameter. The author's contention is the forces are developed at the wetted surfaces only.
[2] Other Resources are listed at the end of this presentation.

of reliable and sound hose designs and manufactured product. Figure 1 reproduces the Evans FBD model showing the forces **H** and **V** as acting directly on each braid strand at diameter, D_m.

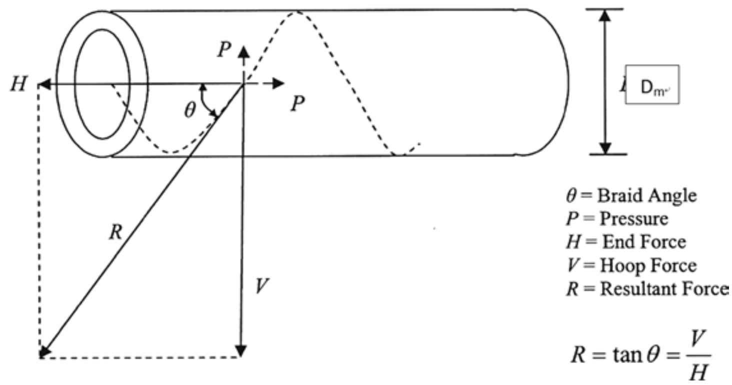

Figure 1
Conventional Free Body Diagram of the Pressure Forces Supported by the Reinforcement.

Chapter 7 of ***Hose Technology*** presents the free body diagram. Evans defines an axial and a radial force and designates them as vectors **H** and **V**. Where **H** is equal to P x D_m^2 x and **V** is equal to P x D_m x L/2. Since these are vectors, we can calculate the magnitude and direction of the resultant vector, **R**.

The Evans analysis features force definitions based on the reinforcement geometry and aligns the forces with the reinforcement spiral angle. The Evan's analysis calculates or estimates braid constructions that have been successfully employed for many hose designs.

2. THE EVAN'S MODEL FOR SPIRAL (AND BRAIDED) HOSE DESIGN

Evan's concludes with the Burst Formula for Braided or Spiral hose. The Evans (Hoop Force) Burst Formula for Braided or Spiral Hose is:

$$P_b = (2 \times N \times \mathbf{R} \times \sin(\theta))/(D_m \times L)$$

Where:

Table 1
Variables Used by Evans

Symbol	Definition
D_m	Mean diameter of the reinforcement
H[1]	Horizontal (or Axial) Force Vector = P_b x D_m^2 x $\pi/4$
L	Pitch or lead length of the spiral
N	Number of reinforcement ends. Dictated by tube surface coverage requirements.
P_b	Hydrostatic Pressure at Burst. This value is measured by experiment.
R	Breaking (tensile) strength of the ligament.
θ	θ = Arctangent(2L/πD) and is defined as the braid angle.. Also Tan(θ) = **V**/**H** = 2L/πD.
V	Vertical (or Radial) Force Vector = P_b x D_m x L/2

Here is the conflict with the Evan's model: The horizontal force calculation is based on the mean diameter of the reinforcement; again, what happens when the tube wall is increased? Consider the following:

Suppose we have a hose tube with a nominal inside diameter of a .25 inch. Then let us apply a pressure of 1000 pounds per square inch. If we choose a tube wall thickness of .030 inch or .050 inch; how much reinforcement do we need to keep the tube from failing? Assume the pitch is such that the reinforcement angle is 54^0 44' and assume the hydrostatic pressure acts at the mean diameter of the reinforcement[3].

The Evans' solution allows us to estimate both the burst value from the equation; and we can estimate the force reinforcement must support; that value is: N x **R**; and this is true for any pressure in between 0 pressure and burst pressure[4]. Why is that? We can rearrange the Evans solution as:

$$P \times D_m \times L/(2x \sin(\theta)) = N \times \mathbf{R}$$

We find: …for the tube with the .030" wall the "N x **R**"

[3] The reinforcement angle of 54^0 44' is the neutral angle. Laboratory Test results support the assertion the reinforcement neither elongates nor expands when the reinforcement lies along the neutral angle.

[4] The Evans solution is of the form: R = constant x P where the constant is based on the geometry of the hose reinforcement construction. R = {D_m x L/(2x sin(θ))} x P. Every value within the brackets is based on geometry.

force is about 130.7 pounds and for the .050” wall tube the “N x **R**” force is around 166.6 pounds. Why should the thicker, stronger tube need a stronger reinforcement[5] design? What is wrong? Let us take a closer look at the Free body Diagram of a hose assembly that includes an end fitting.

3. THE FREE BODY DIAGRAM FOR THE HOSE ASSEMBLY RESPONDING TO HYDROSTATIC PRESSURE.

First, look at the horizontal force created by the fluid pressure. The calculated magnitude is the same as before with one difference. The important diameter is not the braid diameter, D_m; the important diameter is the nipple’s outside diameter, D_n. The horizontal force is developed by the pressure acting directly on the fitting; the braid resists the (sum of the) horizontal force (and the vertical force.)

The horizontal pressure force, **H**, always pushes directly against the fitting’s nipple and if the braid is not connected by the shell or socket, the pressure would push the nipple out of the hose segment. The horizontal force’s magnitude does not change even if the tube wall thickness changes. Here is where the calculation of the reinforcement design requirement changes from that predicted by the Evans model.The size of the reaction force carried by the reinforcement diameter does not change even as the tube wall thickness changes. The reaction force depends on the nipple’s outside diameter and it is carried by the reinforcement[6]; again that force is created by pressure at the wetted nipple diameter!

Next, look at the vertical force, **V**, created by the fluid pressure. Similar to the Evans analysis, the vertical force acts at the inside, or wetted diameter of the tube and does not acts directly upon the reinforcement; the reinforcement carries the pressure driven force developed inside of the tube; and the reinforcement prevents the tube from expanding to failure.

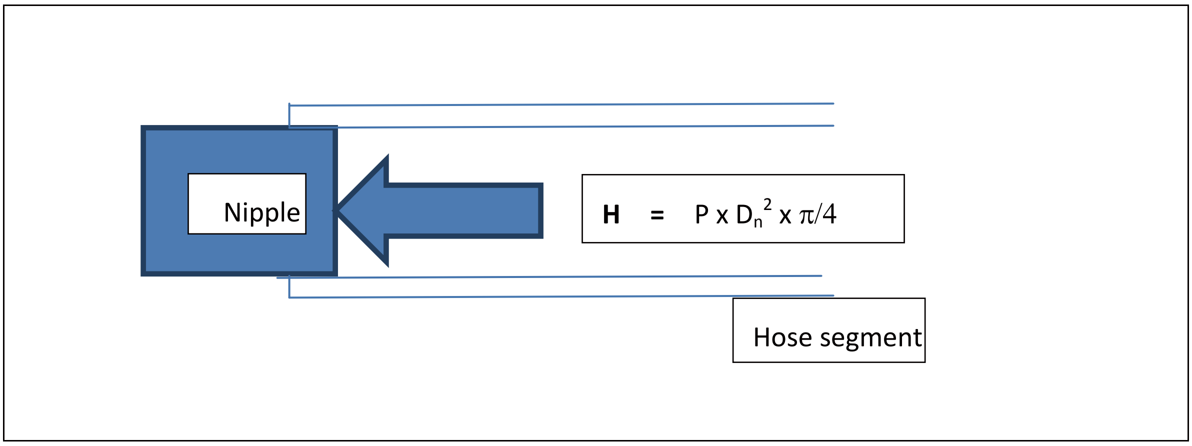

Figure 2
The pressure force, H, acts on the nipple and not directly at “P” as indicated in Figure 1.

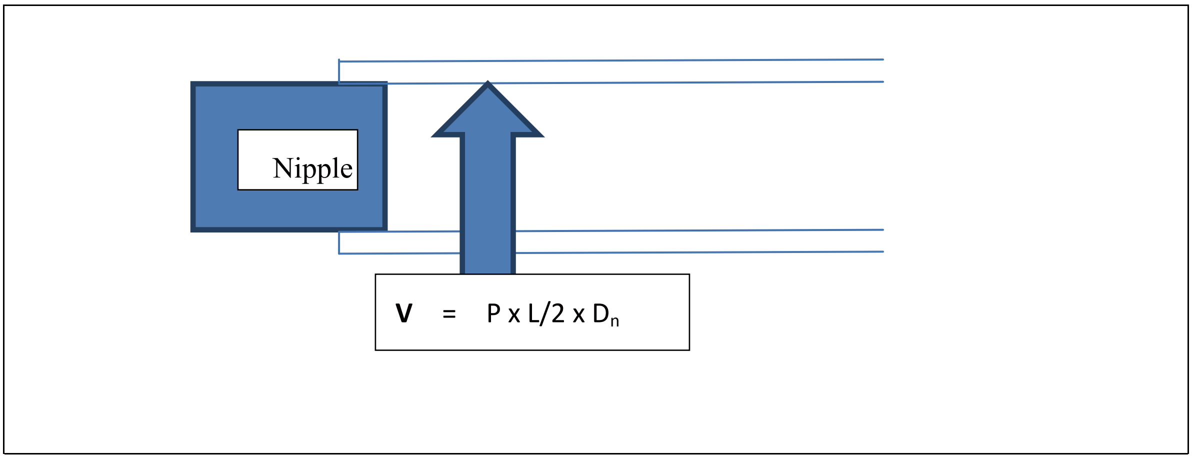

Figure 3
The pressure force, V, acts on the tube’s inside surface and not directly at “p” as indicated in Figure 1.

[5] An elastic tube resists the fluid pressure to the extent of its material capability. Use reinforcement if the tube is not strong enough.
[6] The magnitude and direction of the reinforcement’s horizontal reaction force is: **H** = -R x N x cos(θ).

The physics justifying the moving of the radial force, **V**, to the inside diameter of the tube is two-fold. Firstly, it is a tube and it is trapped between the fluid and the reinforcement. The fluid pushes radially and the reinforcement pushes back with equal force and the tube is trapped in place[7]. Secondly, the lay of the reinforcement is always at the neutral angle. This justification is round-about. We know from experience the reinforcement, when under pressure, always aligns at the neutral angle. So where does the vertical force act? It must be adjacent to the horizontal force so the resulting force created by the vector sum of the horizontal force, **H**, and the vertical force, **V**, lies at the neutral angle.

The recommendation for the analysis method is to change from using the mean diameter of the reinforcement, D_m, as defined by Evan to the nipple's diameter, D_n. Any change to the tube or reinforcement thickness will have no impact on the magnitude of the force the reinforcement must support.

The Evans solution for the direction of the neutral angle as 54^0 44' has been verified by Laboratory length change tests. The braid angle of a pressurized hose assembly moves towards the neutral angle: case 1, if the horizontal force is greater than the vertical force, the hose assembly will elongate until the horizontal and vertical forces are equal and that only happens when the reinforcement braid angle is equal to 54^0 44'; and case 2, if the reverse is true, the hose assembly shortens until the braid reaches the neutral angle.

In summary, the hydrostatic forces, **H** and **V**, form at the wetted surfaces of the nipple and tube; that is, at the nipple diameter and along the related wetted "pitch" inside tube. The resultant force acts along the neutral angle and the magnitude of the resultant is equal to $P \times 1.36 \times D_n^2$; and following Evans analysis, we can conclude: $R \times N = P \times 1.36 \times D_n^2$ and we have created a model whereby we know the design strength of the reinforcement must be equal to $P \times 1.36 \times D_n^2$ and not to $P \times 1.36 \times D_m^2$.

Table 2
Summary of the Engineering Analysis and Design Variable Definitions

Magnitude of the hydrostatic force is equal to $P \times 1.36 \times D_n^2$ when the reinforcement aligns at the Neutral Angle of 54^0 44'

Symbol	Design Variables
D_n	Nipple diameter
H	Horizontal (or Axial) Force Vector = $P \times D_n^2 \times \pi/4$
L	Hydraulic pitch length when the reinforcement moves to the neutral angle
N	Number of reinforcement ends required for tube coverage to prevent a blow-out burst failure. N is determined empirically.
P	Hydrostatic Pressure inside of the tube
R	Breaking (tensile) strength of the ligament.
θ	θ = Arctangent($2L/\pi D$) and is defined as the braid angle; and Tan(θ) = **V**/**H** = $2L/\pi D$.
V	Vertical (or Radial) Force Vector = $P \times D_n \times L/2$

The basic reinforcement design equation is: $R \times N = P \times 1.36 \times D_n^2$ where the number of reinforcement ends, N, must provide sufficient surface coverage to prevent tube failure.

The Evans approach is conservative however, if the customer wants a lighter weight yet strong hose assembly that is designed using the smaller forces predicted by the nipple's diameter. This suggested approach to finding a more efficient hose construction based on the forces generated at the fluid's boundaries promise the next generation hose design.

4. HOSE REINFORCEMENT DESIGN THEORY FOR OPTIMIZATION

The hose reinforcement design is reduced to R x N. We calculate the hydrostatic force based on the nipple's diameter and we know the braid angle. Now the designer selects the solution for R x N based on the following criteria:

N, or the necessary number of reinforcement ends has a minimum value that must provide sufficient coverage of the surface of the hose tube to prevent it from extruding between the reinforcement strands. The type of reinforcement braid is selected based on empirical data.

R, or the necessary minimum strength of the reinforcement depends either on the minimum number of strands needed to provide sufficient tube coverage.

There is another condition that must be met: **R** x **N** > $P_b \times 1.36 \times D_n^2$ for the reinforcement design as selected; the product of **R** x **N** that is reinforcement strength times reinforcement end calculated quantity must be greater than the minimum burst pressure required by the design. This adds another complication to the design. The implication: Each strand, N, shares the same tension, R. The geometric solution for R x N may require two or more layers of reinforcement to keep the hose tube from failing.

[7] Hydrostatic pressure times the area on the inside diameter of the tube is balanced by the reinforcement pressure x area on the outside diameter of the tube. The vertical forces are at equilibrium. The magnitude and direction of the vertical reaction force is: **V** = -R x N x sin(θ).

CONCLUSION

The Evan's analysis is successful because it is conservative. The recommendation from the analysis is based on using the mean braid or spiral diameter as the boundary for generating the hydrostatic force.

However, the free-body-diagram indicates the horizontal force is generated by the pressure acting directly upon the nipple. The effect is that the horizontal force magnitude is reduced as is the corresponding vertical force; and those reductions allows the designer to more appropriately pick the reinforcement based on coverage or force requirements that may be lighter and more flexible than the Evan's model suggests.

Aside: the tube provides some design strength. The tube's inherent pressure carrying capacity adds safety margin to the reinforcement design calculation.

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